INSTITUT FÜR THEORETISCHE PHYSIK (ITP)
INSTITUTE FOR THEORETICAL PHYSICS (ITP)
Max-von-Laue Str. 1, D-60348 Frankfurt am Main, Germany

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Prof. Dr. Luciano Rezzolla
Director, Institute for Theoretical Physics
Chair of Theoretical Astrophysics, Institute for Theoretical Physics
Senior Fellow, Frankfurt Institute for Advanced Studies,
Max-von-Laue Str. 1, D-60348
Frankfurt am Main, Germany

Prof. Dr. Piotr Źycki,
NCAC Director
Prof. Dr. Ryszard Szczerba,
Chairman of the Scientific Council
Nicolaus Copernicus Astronomical Center (NCAC),
Warsaw, Poland

Frankfurt, June 6, 2017

Dear Prof. Źycki, Dear Prof. Szczerba,

What follows is my evaluation of the Ph.D. Thesis of Mr. **Bhupendra Mishra**, entitled *General relativistic simulations of luminous and non-steady accretion flows*.

The Thesis reports the research work carried out during the PhD studies and covers a very active and interesting area of research in relativistic astrophysics, namely, the study of accretion flows onto compact objects in general relativity. Although this area has been the subject of studies for decades now, the wealth of new results presented in the Thesis is a testimony to the fact that this area still offers many opportunities for novel and interesting discoveries.

Overall, the Thesis collects the results of four distinct investigations, each of which has seen the publication of an article on a prestigious journal (MNRAS and A&A) and which Mr. Mishra has led as first author. Because of the considerable differences that accompany the various investigations, I will comment below on each of them separately.

- *"A geometrically thin accretion disc around a Maclaurin spheroid"*, Mishra and Vaidya (2015). This article developed a semi-analytic and numerical model to study a geometrically thin and optically thick accretion disc around a Maclaurin spheroid. In particular, the effects of rapid rotation of the Maclaurin spheroid on the disc structure were analysed in detail and how the disc parameters depend on the eccentricity of the spheroid. The semi-analytic results obtained showed that an increase in the eccentricity of the spheroid has the same behaviour as a decrease in the mass-accretion rate; in particular, if the eccentricity of an accreting object is high, the matter will diffuse more slowly during its viscous evolution. This result, albeit obtained in a rather idealised framework, has the value of providing an explanation of how spin-up or spin-down of the accreting object can change the time evolution of the accretion disc, and that the changes in emission spectra can be used to determine the eccentricity, and thus the period of the spheroid.

- *"Three-dimensional, global, radiative GRMHD simulations of a thermally unstable disc"* Mishra et al. (2016). This article reported the first global three-dimensional general-relativistic radiative magnetohydrodynamical (MHD) simulations of geometrically thin accretion discs with the goal of testing their thermal stability. In particular, two cases have been analysed in great detail: one that is initially radiation-pressure-dominated and another that is initially gas-pressure dominated. Upon performing the numerical simulations, it was indeed found that in the radiation-pressure-domina-ted disc, cooling dominates over heating, causing the disc to collapse vertically as a result of what appears to be a thermal instability. On the other hand, and as expected, the gas-pressure-dominated model was found to be stable, with heating and cooling roughly in balance. The importance of this work has been that of confirming, through fully nonlinear and three-dimensional numerical calculations, the results of simplified analytical calculations of the thermal instability. This work has also exposed Mr. Mishra to the complexities of large-scale general-relativistic MHD codes.
- *"Relativistic effects on radiative ejection of coronae in variable X-ray sources"*, Mishra and Kluzniak (2016). This paper is dedicated to the study of the mechanisms that lead to the ejection of accretion-disc coronae around neutron stars suffering an X-ray burst. The analysis was performed investigating the motion of a test particle in a spherically symmetric radiation field and within a general-relativistic spacetime for the star. The authors found that at every radial distance from the star larger than the innermost stable circular orbit, and for any initial luminosity of the star, there is exists a luminosity increase (a "burst") that will result into the ejection of the corona. In particular, this luminosity is much higher and close to the Eddington luminosity in the inner parts of the optically thin neutron-star corona, while at larger distances (e.g., of 20 gravitational radii or more) a sub-Eddington outburst is sufficient to eject the outer parts of the corona. Particularly interesting is the finding that mildly fluctuating luminosities lead to dissipation in the plasma, thus providing a possible explanation for the observed X-ray temperatures of coronae in low-mass X-ray binaries.
- *"Quasi-periodic oscillations from relativistic ray-traced hydrodynamical tori"*, Mishra et al. (2017). I regard this last article as the most impressive contribution to the Thesis. In it, in fact, Mr. Mishra and his collaborators performed two-dimensional hydrodynamical simulations of a torus around a Schwarzschild black hole. The torus was perturbed by making use of a number of different perturbations and the dynamics of the oscillating torus, namely in terms of its quasi-periodic oscillations (QPOs), was then associated with the eigenmode classification of so-called "slender tori" – these are tori with evanescent and circular cross section. In addition, relativistic ray-tracing was used in a post-processing step of the hydrodynamical simulations to compute the light curves and interpret the QPOs in torus. Besides performing an impressively complete analysis of this problem, the importance of this work is to be found in the fact that it clarified a number of issues that revolved around the QPOs of oscillating tori. These issues originated from the fact that such QPOs have been investigated in different contexts and with different approximations by different authors; this resulted in a diversified and often confusing classification scheme that made it difficult to compare the results of different groups. However, as a result of this investigation, Mr. Mishra was able to conclude that the "radial" and "plus" modes as defined within the slender-tori classification, actually coincide with the fundamental and first overtone (f and o_1) pressure modes previously discussed in the literature. As a result, this work can be seen to close almost a decade of studies dedicated to the QPO oscillations of tori around black holes.

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All of the papers presented in the Thesis are well written and pleasant to read. All aspects are treated clearly, with a detailed discussion of the previous results in the literature, an accurate presentation of the results obtained. However, since the actual Thesis does only little more than binding together the printouts of the published papers – incidentally, this is a option that is not allowed at the Goethe University in Frankfurt–, it remains difficult to asses what is the contribution of Mr. Mishra to the actual writing of the text. I will assume that because he is also the first author of the publications discussed above, Mr. Mishra is also the editor of the text and of the discussions presented in the articles. This, however, remains an assumption and it would have been much better if an effort was made to go beyond a simple binding of papers.

All things considered, the results presented in the publications are rather impressive, both for the breadth of topics covered and for the range of techniques used, that range from simple analytic estimates to full-fledged three dimensional numerical simulations in general-relativistic MHD. In all of these papers Mr. Mishra is the first author; at the same time, he has managed to collaborate with a number of excellent scientists from international institutions. This reveals an advanced maturity in addressing modern research.

All of these considerations clearly point to the same conclusion: Mr. Mishra has clearly shown an ability for creative and interesting scientific work, and is well qualified for a Ph.D. degree. The Thesis satisfies amply the customary requirements of a Ph.D. Thesis and I recommend the candidate to be allowed to present the Thesis in a **public defence**. Finally, given the very high quality of the results presented, I am glad to recommend that the Diploma be granted with **distinction** ("z wyróżnieniem").

Sincerely,

Luciano Rezzolla